NASA TECHNICAL NOTE **NASA TN D-4585**

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NASA TN D-4585

A HAND-HELD SEXTANT QUALIFIED FOR SPACE FLIGHT

by Bedford A. Lampkin and Donald W. Smith

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1968

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SUMMARY

A hand-held sextant has been developed and fabricated for use in space navigation. The instrument is space-flight rated. Experienced operators may obtain measurement data having an accuracy of better than 10 seconds of arc.

The mechanical, optical, and electrical characteristics of the instrument are described in detail. A synopsis of the results of the environmental tests to which the instrument was subjected and a mechanical error model of the instrument are presented. Measurement data and analysis are presented which indicate the operational accuracy of the sextant.

INTRODUCTION

For over 200 years, the sextant has provided navigators with a means for determining the height of celestial bodies above the local horizontal plane. The characteristics of reliability, accuracy, and independence of external electrical power which have made the sextant useful in the past also enhance its usefulness as a device for space navigation.

In the past 30 years, most advancements to sextant technology have been applied to the instruments used in aerial navigation. The measurement accuracy expected of these instruments is approximately 1 minute of arc. More recently, the possibility of using a hand-held sextant in space navigation has been examined. This use required an advance in sextant measurement accuracy and in the ability of the instrument to withstand a hostile environment. Reference 1 is one of the earliest reports describing a hand-held sextant that might be used in space navigation. The measurement accuracy of this instrument was approximately 40 seconds of arc. Reference 2 describes a more advanced version of this same instrument and in reference 3 an interesting concept of a photographic sextant for space navigation is examined.

To explore the possibility of using a sextant in space navigation, an experiment was designed which could be conducted on-board a Gemini spacecraft in earth orbit. The primary purpose of the experiment was to evaluate the effect of the space environment on the measurement performance of the astronaut. The experiment was designed to simulate a midcourse navigation

measurement task. The implication of this assumption was that the accuracy goal of measurement performance was 10 arcsec as suggested in reference 4.

At the outset the instrument described in references 1 and 2 was not available, and it was determined experimentally that no commercially available sextant would meet both the accuracy and environmental requirements of the experiment. Therefore, an instrument was designed and fabricated specifically for the experiment. The most stringent requirements on the design of the sextant concerned the accuracy and the operating environment of the instrument. The significance of the operating environment is that the sextant must be space-flight rated and must be small and lightweight so that it can be stored and operated within the spacecraft. An abstract of the specifications for procuring the sextent is presented in appendix A.

The purpose of this report is to document a summary of characteristics and qualifications of a sextant which represents a significant advance in the state of the art. The instrument is unique, not because of any one feature, but because all of its elements have been designed and fabricated to produce a sextant that combines structural integrity, minimum size and weight, and operational accuracy and convenience, making it well suited for space navigation.

Included in the report is a description of the sextant and its operating procedures and a summary of the environmental tests performed in qualifying the instrument for space flight. More detailed information concerning these items may be found in references 5 and 6, respectively. An error model of the operating components of the sextant is presented. Tests have verified the functional effectiveness and operational accuracy of the sextant, and data from these tests are included in the report.

DESCRIPTION OF THE SEXTANT

The description of the sextant includes a summary of the mechanical, optical and electrical properties of the instrument. The calibration procedures and instrument accuracy specifications are summarized in appendix A. The sextant and its operation are described in detail in reference 5, and the test procedures to qualify the sextant for the specification in appendix A are described in reference 6.

Mechanical Properties

The sextant is equipped with a normal eye relief and a long eye relief eyepiece. The normal eye relief eyepiece permits normal operation of the sextant with the eyepiece placed against the operator's eye socket. The long eye relief eyepiece permits operation of the sextant with the spacesuit pressurized and its visor in position between the sextant and the sextant operator. Each eyepiece contains its own focusing mechanism and diopter scale.

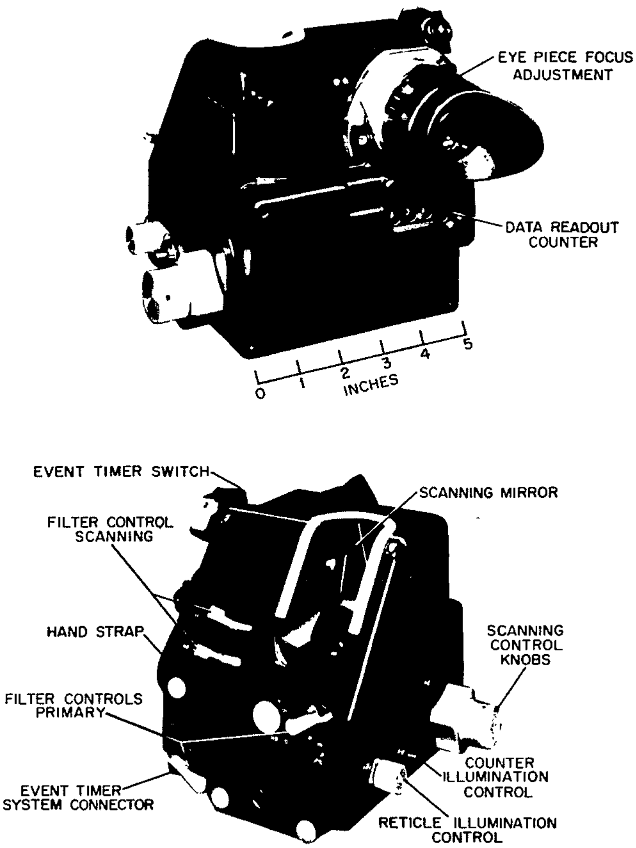


Figure 1.- Hand-held space sextant.

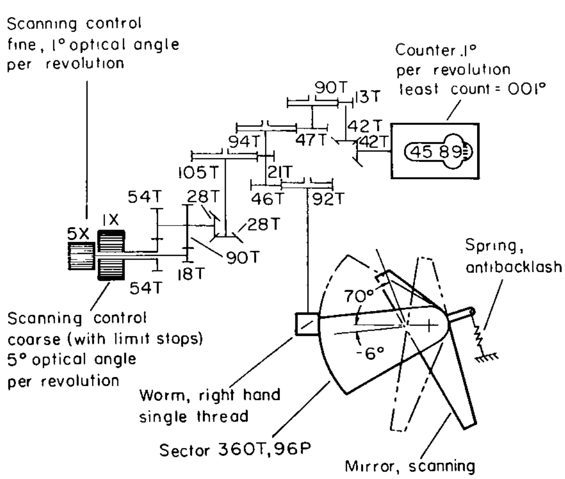


Figure 2.- Schematic diagram of gear train for scanning control and data readout.

The normal eye relief eyepiece has a rubber eyeguard contoured to fit comfortably against the operator's eye socket. The long eye relief eyepiece contains a flexible circular eyeguard that adjusts to the curvature of the spacesuit visor.

Table I gives the nominal dimensions and weight of the sextant with either eyepiece together with dimensional outline drawings of the sextant. Photographs of the sextant are shown in figure 1 with the operating controls noted. Figure 2 is a schematic diagram of the gear train which links the scanning mirror and readout device.

The sextant is equipped with an event timer switch. This button switch provides a timing pulse on the spacecraft recording system at the time of sextant angle measurements.

The sextant measured angle is displayed on the "counter" below the eyepiece. The least count of the display is 0.001°. Two miniature red lamps illuminate the counter.

The scanning control uses the gear train (fig. 2) to position the scanning mirror and readout counter. Both the fine and coarse control are mounted concentric to the same shaft and are geared so that a full revolution of the coarse control rotates the mirror 2.5° (equivalent to 5° measured angle). Rotating the fine control one full revolution rotates the scanning mirror 0.5° (equivalent to 1° measured angle).

There are filter controls for each line of sight. Choices of neutral density filters are available and may be inserted into each line of sight to reduce the transmitted light intensity. In the fixed line of sight, either filter ND-1.0 or

ND-1.6 is used to reduce the transmitted light by a factor of 10 or 40, respectively. In the scanning line of sight, either filter ND-1.0 or ND-1.3 is used to reduce the transmitted light by a factor of 10 or 20, respectively.

A control is provided for adjusting the telescope reticle illumination. The "counter" illumination control is also provided with a spring-loaded on-off switch. The battery operating the reticle and readout lights is recessed into the bottom of the sextant. The battery may be replaced by removing its cover plate.

Optical Properties

Functionally, the sextant is divided into two optical systems: the telescope and the target acquisition optical system. As in any telescope, the essential optical elements are an objective lens with the function of forming an image of object space at the principal focus, and an eyepiece through which the observer views this image. The principal or normal eye relief eyepiece is a wide angle eyepiece of the Erfle type with a 25.4-mm focal length. It provides a magnification of 8.0. The second eyepiece with long eye relief is mechanically interchangeable with the first and is necessary when the astronaut takes sextant measurements with his helmet visor in place. This eyepiece provides a magnifying power of 4.6. The true field of view of the telescope is 7° with either eyepiece. The two mirrors and prism in the sextant telescope permit packaging of the instrument in a small volume and serve to erect the images observed by the astronaut.

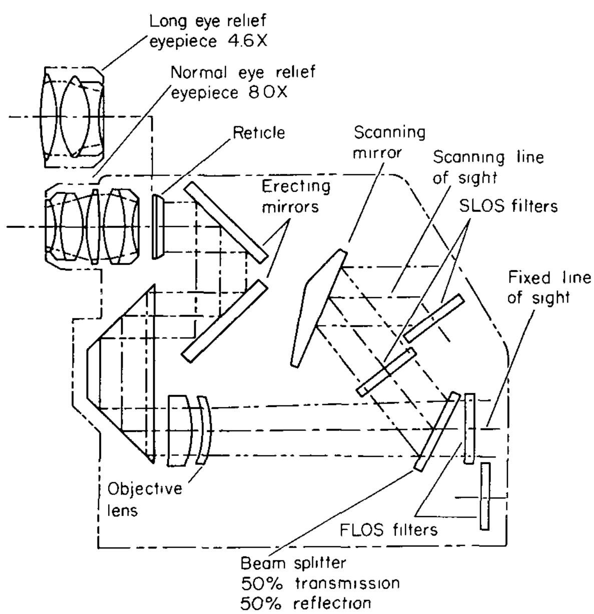


Figure 3.- Optical schematic diagram of sextant.

A reticle pattern is engraved in a thin glass plate at the principal focus of the objective lens. The reticle pattern may be observed in the telescope field of view because of light reflected by the engraved lines from a light source provided by the sextant electrical system.

The target acquisition optical system includes the following optical elements: A beam splitter, a scanning mirror, and four filters, two of which may be selected for each line of sight. The beam splitter is coated to provide approximately 50-percent transmission through each line of sight. The scanning mirror is designed to reflect the scanning line of sight through a range of 76°.

Table I includes various optical characteristics of the sextant. Figure 3 is a schematic diagram of the sextant optical system.

Electrical Properties

The electrical system of the hand-held sextant illuminates the readout counter and illuminates the reticle lines so that they are easily discernible in a darkened environment. The schematic diagram of the electrical system is shown in figure 4. The energy source for the illumination circuit is

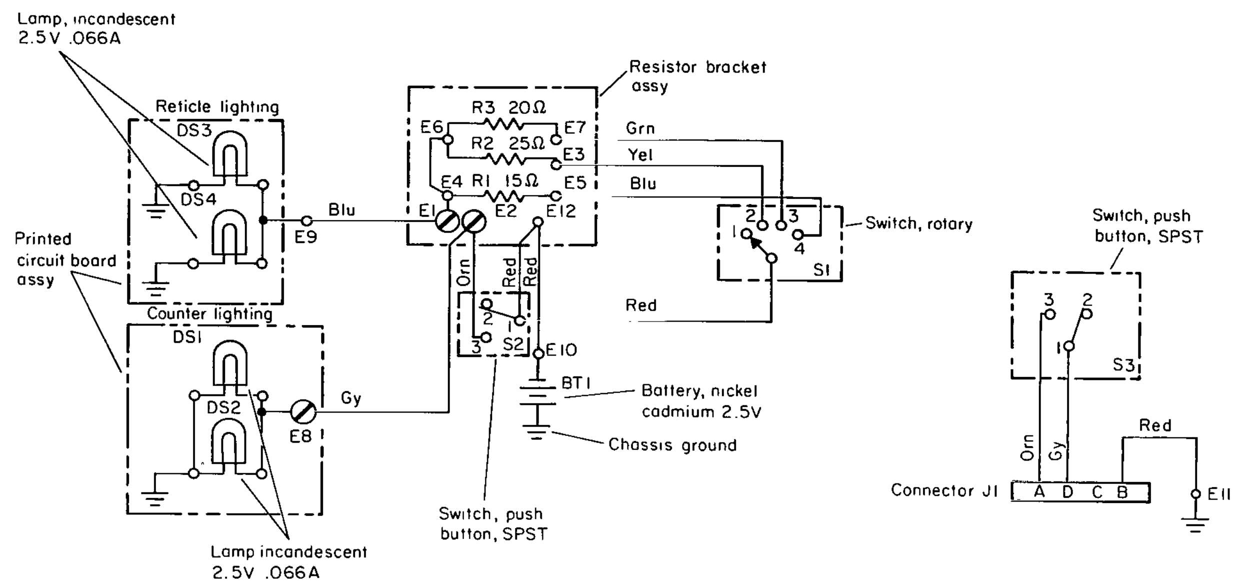


Figure 4.- Electrical schematic diagram of sextant.

self-contained and consists of a dual cell rechargeable, nickel-cadmium battery qualified for space flight. The reticle illumination circuit consists of two parallel lamps and a four-position rotary switch. The switch is used to adjust the level of illumination and also has an "off" position to open the circuit. Two reticle lamps provide even illumination and increase reliability. The circuit that illuminates the readout counter consists of a pair of red lamps that are activated by a push-button switch.

The timing circuit, also shown in figure 5, consists of a push-button switch and a connector to the spacecraft time recording system.

ENVIRONMENTAL QUALIFICATION TESTS

Upon assembly, sextant serial no. 2 was subjected to the series of tests specified in appendix A and the space-flight qualification tests (table II) required by the Gemini Program Office. The flight qualification tests are described in reference 6.

The flight qualification requirements of the sextant involved subjecting the instrument to two different series of tests. The first series of tests simulated the launch and flight environment in which the instrument was required to maintain its calibration accuracy. The second series were overstress tests in which the major goal was to expose design deficiencies.

The first series of tests included the following environments.

1. Shock

2. Acoustic noise

3. Acceleration

4. Random vibration

5. Sinusoidal vibration

After each environment, the instrument was inspected in accordance with an abbreviated test procedure (ref. 5) and calibrated in accordance with the specification requirements. No significant changes occurred in the performance calibration or configuration of the instrument as a result of these tests.

In the second series of tests the instrument was subjected to the following environments.

1. Temperature/pressure cycling

2. Decompression

3. Low temperature

4. High temperature/100 percent oxygen atmosphere

5. Shock

6. Humidity

After exposure to each environment, the instrument was subjected to visual and functional testing to detect changes in instrument performance and operation. Only in the humidity test was there a significant change in instrument performance.

The humidity test was the last test. Inspection after a 24-hour exposure to the humidity and elevated temperature environment revealed a binding condition in the scanning mirror drive system. The cause of the failure was found to be a hygroscopic plastic that had been used in the fabrication of a data readout gear. The gear was replaced with a gear identical in configuration but fabricated from a material less susceptible to moisture swelling. The instrument was then retested for functional operation and resubmitted to the

humidity environment. The test lasted 240 hours with intermediate functional inspections after each 24 hours. After each intermediate period, and upon completion of the full test, the instrument successfully passed the functional examinations.

SEXTANT ACCURACY

Calibration Results

The requirements for the optical calibrations of the sextant's mechanical gear train are given in paragraph 9.0 of appendix A. The data from these calibrations may be found in reference 6. The calibration as dictated in paragraph 9.0(a) of appendix A indicates that the standard deviation (σ) of the zero position repeatability of the scanning mirror is 0.4 arcsec. Typical results of the calibration as dictated in paragraph 9.0(b) of appendix A are given in table III. It can be seen that the calibration errors are contained within a 20 arcsec envelope and are repeatable to within 6 arcsec. The calibration data obtained as specified in paragraph 9.0(c) of appendix A are given in table IV. These data are contained within a 10 arcsec envelope and are repeatable to within 2 arcsec. Paragraph 9.0(c) of appendix A specifies a calibration between 31° and 32° at 0.1° intervals. The error characteristics determined during this calibration are superimposed upon the gross calibration results from the 1.0° interval calibration. One full rotation of the vernier control knob will change the measured angle 1°. It is assumed that the error characteristics of the 0.1° interval calibration will repeat during each 1° interval throughout the measurement range.

The requirements for the resolving power of the sextant telescope are given in paragraph 3.0 of appendix A. Each telescope was tested and optical resolution with the normal eye relief eyepiece was at least 7.5 arcsec and with the long eye relief eyepiece at least 13 arcsec.

A determination of the zero bias of each optical filter is specified in paragraph 9.0(d) of appendix A. Typical zero bias data for the installed optical filters is given in table V.

Sextant Error Model

The error model in figure 5 was used by the contractor in the design analysis of the sextant so that components contributing relatively large errors could be detected and improved. The sources of errors are inaccuracies developed in the information chain. The individual error sources are analyzed in appendix B. In figure 5, the block diagram indicates the sequence of errors in the information chain and the value of the measurement error associated with each error source.

It is assumed that for this analysis, the error sources are independent and the total measurement error is indicated by the square root of the sum of

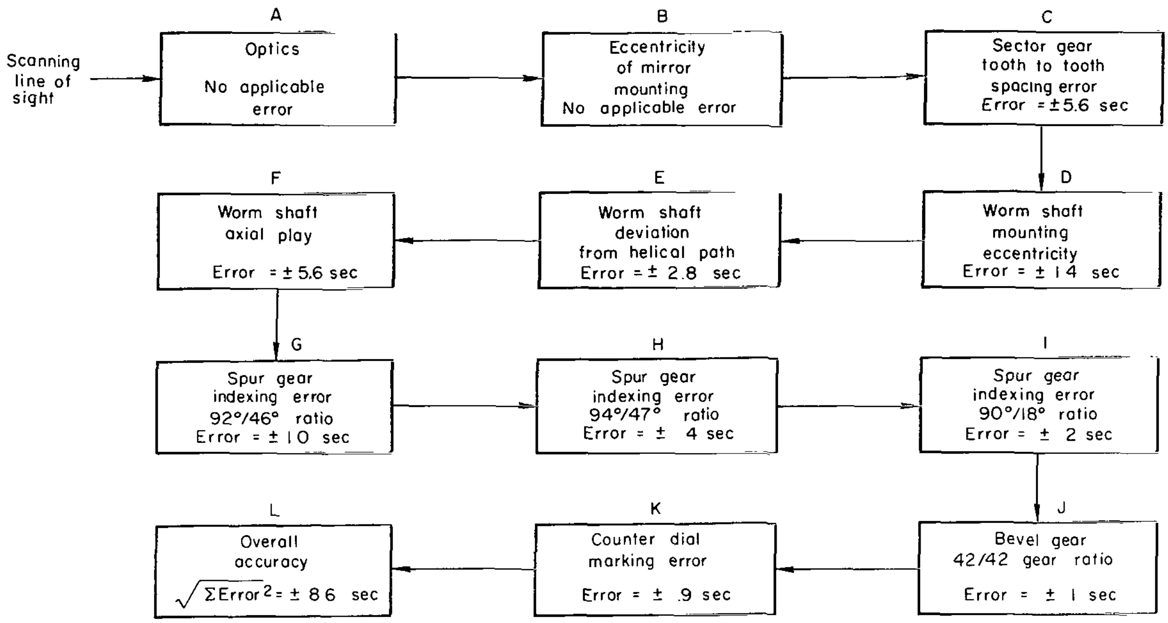


Figure 5.- Sextant error model.

the individual errors squared. In the following tabulation, the maximum value of each individual error obtained in the analysis of appendix B and the resulting total error are presented. The total RMS value is 8.6 arcsec, indicating that from the assumptions the maximum error value that may be contributed to the mechanical components of the sextant is expected to be 8.6 arcsec.

Source of error	Maximum error, arcsec	(Maximum error)^2
A. Optical Error	N/A	
B. Eccentricity of mirror mounting	N/A	
C. Sector gear tooth to tooth spacing error . .	5.6	31.36
D. Worm shaft mounting eccentricity	1.4	1.96
E. Worm shaft deviation from helical path . . .	2.8	7.84
F. Worm shaft axial play	5.6	31.36
G. Spur gears indexing error (92/46 gear ratio).	1.0	1.00
H. Spur gears indexing error (94/47 gear ratio).	0.4	0.16
I. Spur gears indexing error (90/18 gear ratio).	0.2	0.04
J. Bevel gears indexing error (42/42 gear ratio)	0.1	0.01
K. Counter dial readout error	0.9	0.81
Total	18.0	74.54

RSS value = $\sqrt{74.54}$ = 8.6

FUNCTIONAL VERIFICATION TESTS

The contractor conducted a functional verification test using sextant serial no. 1 to verify the operational accuracy of the sextant as specified in appendix A paragraph 8.0. The test was made on four consecutive nights at the Steward Observatory of the University of Arizona. Each night various sighting measurements were obtained. During each sighting session, 10 consecutive measurements were obtained by one of four operators using the same sighting targets. Measurements were obtained for target combinations of a star and a star, a star and lunar limb, and a lunar limb and opposite lunar limb.

The backgrounds of the four individuals who obtained the measurement data differed. However, each was employed in a technical capacity. Subjects 1, 3, and 4 had substantial experience in using a two-line-of-sight marine sextant. Subject 2 had no previous experience in using a sextant.

From each sighting session, the standard deviation and the mean measurement error of the 10 measurements were computed. The standard deviation indicated the distribution of the 10 measurements about the mean value. The mean measurement error was the mean measured angle less the computed target angle. The computed angle was computed for each time at which a measured angle was obtained. The computed angle was corrected for annual aberration and atmospheric refraction. Atmospheric refraction was computed for a standard atmosphere based on conditions at the sighting station. For this purpose, the temperature at the test site was recorded at hourly intervals and the barometric pressure was established from the local weather bureau. The computing program (ref. 6) used to predict the measured angle is expected to be accurate to within 1 arcsec. The program has been compared favorably with similar programs and has been used extensively for various celestial targets and sighting conditions.

An electronic clock was used to establish the precise time at which each measurement was taken. The sextant event timer switch was connected to the clock printout circuit and was used at each measurement. It is estimated that the recorded time was accurate to within ±0.5 sec.

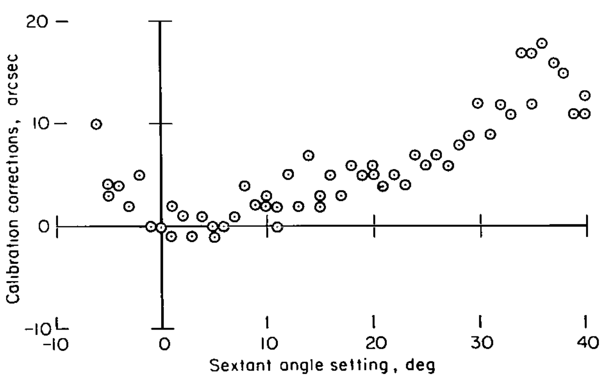


Figure 6.- Sextant no. 1 calibration data.

The measurement data were corrected for the sextant calibration (fig. 6) the filter calibration (table V(a)) and the zero bias data of the instrument (table VI). The sextant and filter calibration data were supplied by the contractor. The zero bias data were obtained on three of four nights of the test period.

The technique for obtaining the zero bias data was to have the observer obtain the image of the

same star in both lines of sight. The zero position was detected by adjusting the scanning line of sight until the two images were effectively superimposed in the telescope field of view. At this time, the measured angle was recorded. To facilitate this measurement, the sextant had been adjusted at assembly so that when the two lines of sight were parallel, the two images in the telescope field of view were displaced laterally rather than being superimposed. In previous experiments, it had been determined that the two sextant lines of sight could be adjusted parallel more accurately by bringing the two star images (each image received from a single line of sight) to the same height in the telescope field of view rather than superimposing statically one star image over the other. The lateral displacement was slight enough that at the zero position, the two images could be individually resolved. Five measurements were recorded when the scanning line of sight was adjusted in the positive direction and five measurements were obtained with the adjustment in the negative direction. In each case, the five measurements were averaged and the appropriate zero bias correction was applied to the angle measurements. The average zero bias value in table VI is approximately -8 arcsec, indicating that typically, the measured angle must be increased by 8 arcsec to be correct. In practice, zero bias data are obtained by each individual and applied to his measurement data.

Measurement data obtained during the functional verification tests are presented in table VII. The appropriate corrections are applied. The uncorrected measurement error is defined as the measured angle less the computed angle. The uncorrected mean error is the average uncorrected measurement error obtained during a single sighting session. The σ value is defined as the standard deviation of the individual measurement errors about the mean error.

In figure 7, the standard deviation scores for each subject are shown for the sequence of sighting sessions between the following target pairs: a star and a star, a star and a lunar limb, and a lunar limb and a lunar limb. The measurement scores of all subjects with each target pair combination reached the specified limit (appendix A) of 10 arcsec by the final day of the test period. Apparently the less experienced operators underwent a learning process early in the test period. However, by the final test day, all the subjects performed with similar measurement accuracy.

In figure 8, the average of the mean errors $(\bar{\varepsilon})$ and the average standard deviation $(\bar{\sigma})$ obtained during the final two days are presented for measurements between a star and a star, a lunar limb and a lunar limb, a star and a near lunar limb, and a star and a far lunar limb. These data are for all operators, and, in each case, the standard deviation is well below the specification limit of 10 arcsec. The largest mean error of approximately 12.3 arcsec was obtained between a star and a far lunar limb. The mean error between the star and near lunar limb was approximately 0.7 arcsec.

Irradiance is suspected as being responsible for a portion of the measurement error when the lunar limb is used as a sighting target, for it causes bright objects against a dark background to appear larger than they truly are. As the contrast between the bright object and the dark background increases,

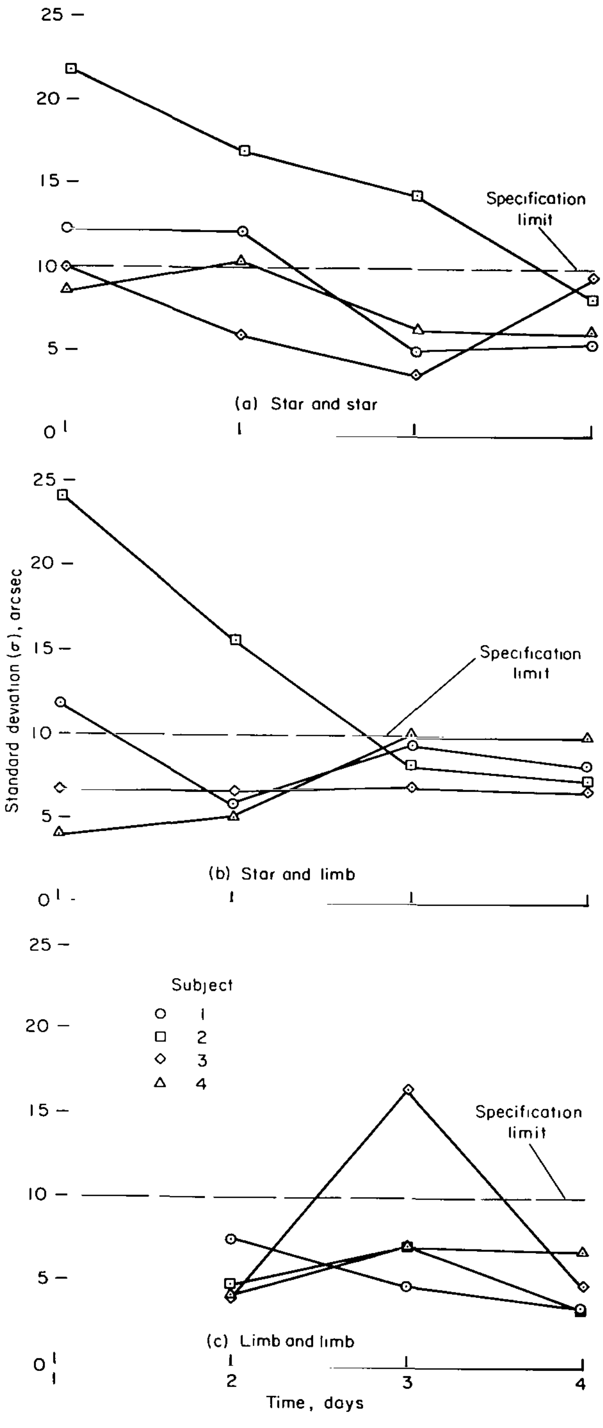


Figure 7.- Standard deviations of measurements obtained during the functional verification tests.

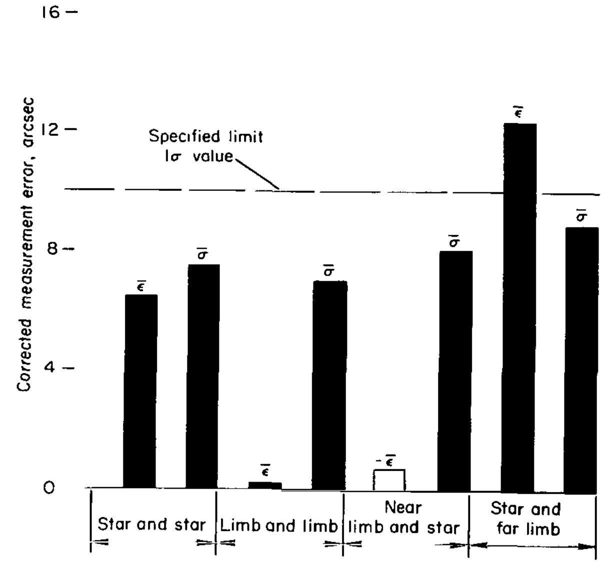
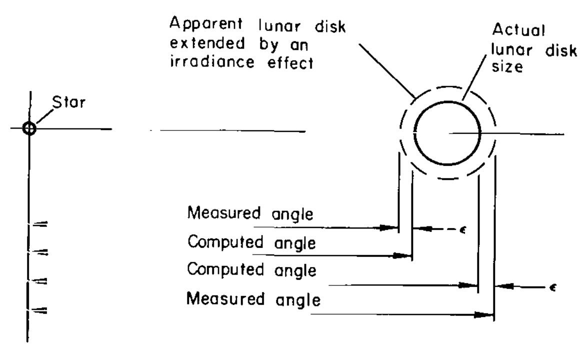


Figure 8.- The average measurement error characteristics obtained during the final two days of the functional verification tests.

the apparent size of the bright object increases. For a measurement between a star and a lunar limb, the star would be superimposed upon the extended lunar limb. The following sketch indicates the manner in which



irradiance might introduce errors into sextant measurements of the included angle between a star and either limb of a full moon. In figure 9, measurement bias errors between a star and a lunar limb are presented for each sighting session and for each subject. Figures 9(a) and 9(b) give the measurement data between a star and a near limb and between a star and a far limb,

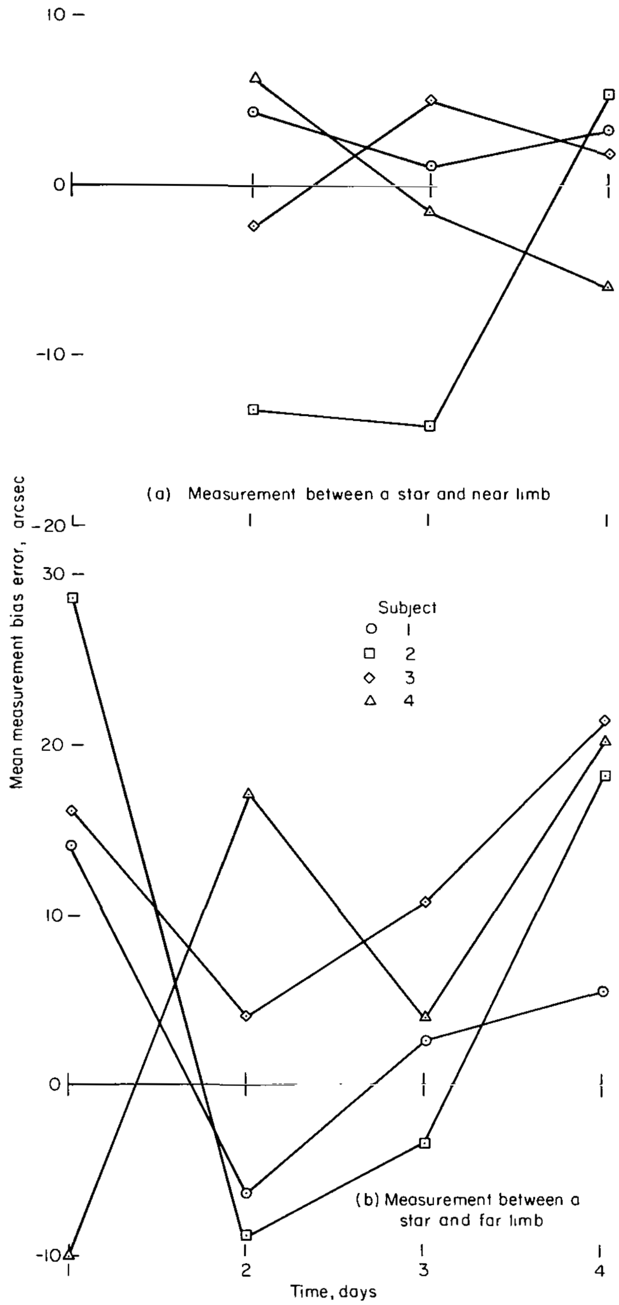


Figure 9.- Star-lunar-limb measurement bias errors.

respectively. For each type of measurement, the bias errors have large variations between sighting sessions and between subjects. It was expected that the bias errors would be symmetrical about the moon, but figure 9 shows that the average error between the star and far limb measurements is larger than the average error between the star and near limb measurements.

CONCLUSIONS

A hand-held sextant designed for use in space navigation and representing a significant advance in the state of the art has been described. A synopsis of the environmental tests undergone by the instrument and the results of the flight qualification tests are presented. Functional verification test data are presented and an error model based upon an initial design analysis is described. An abstract from the sextant contract specifications is presented in appendix A. The following conclusions are based on the measured performance.

1. The instrument described herein meets the specifications of appendix A.

2. Measurement data accurate within 10 arcsec may be obtained by an experienced operator.

3. The instrument has successfully undergone the necessary environmental tests to be space-flight rated.

4. An inexperienced operator may be trained to use the sextant with near optimum performance in a 4-day period.

5. When the moon is used as a sighting target, the apparent irradiance may introduce a significant measurement error and would appear to be the proper subject of further investigation.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Feb. 20, 1968
125-17-02-10-00-21

APPENDIX A

ABSTRACT FROM SEXTANT CONTRACT SPECIFICATIONS

1.0 General

The basic requirement is the design, development and manufacture of a tool for measuring the angle between the lines of sight to two known stars, a star and a lunar limb or landmark, or two opposite lunar limbs. Such measurements are to be made through the window of a Gemini spacecraft which will be in orbit about the earth. The operator of the instrument will be wearing either a pressure suit with a helmet, the visor of which may be open or closed, or an inflated pressure suit with the visor closed.

The instrument must combine reliability, ease of operation and readout, accuracy of measurement, and minimum volume and weight. The operator will be relied upon for instrument operation including target acquisition and superposition, angle readout, and operation of timing equipment.

2.0 Mechanical Design

The sextant shall be a hand-held instrument during actual operation in the spacecraft. When the operator is seated in the Gemini spacecraft, the distance along the line of sight between the inner surface of the window and the outer surface of the helmet visor is 8 inches. With the visor up, the dimension between the astronaut's eye and window inner surface along the line of sight is 10 inches. The instrumented components arranged in the line of sight are strictly limited by these dimensions. The window is inclined approximately 45° to the line of sight; therefore, the line-of-sight dimension is not the limiting dimension when the volume of the instrument is taken into account. The maximum distance between the two lines of sight where they pass through the window is limited to 6 inches. The design goal of instrument weight is 5 pounds and will not exceed 8 pounds. The instrument must be operable while the astronaut is wearing the pressure suit either inflated or uninflated.

The instrument will be required to operate satisfactorily in a partial vacuum (3.5 psia) in a weightless condition after being exposed to a pressure of 10^{-5} mm Hg for 48 hours. The instrument is also required to operate satisfactorily in an orbit altitude vacuum (10^{-5} mm Hg).

The mechanical design shall be such that the instrument will be protected from damage due to contact with wall, windows, and other like pieces of hardware during typical handling exercises in the spacecraft.

The instrument must be flight-rated in accordance with the testing schedule shown in table II. At the completion of the flight rating tests, the instrument during calibration must perform within a 1 σ error of 6 arcsec based on a calibration prior to the flight qualification tests. If packaging is required to flight qualify the instrument, it shall be provided and it will add a minimum volume and weight to the bare instrument. It should be recognized that stowage volume on the Gemini vehicle is at a premium and every effort should be made to keep the package small. Only one instrument must be subjected to these tests and if successful, all identical instruments may be considered space-flight rated.

3.0 Telescope

The telescope is required to have a magnification of 8 power without eye relief optics and a minimum field of view of 7°. Attachable eye relief optics must be provided in addition to the basic telescope in order to utilize the maximum field of view when the astronaut is wearing the pressure helmet with the visor down in which case the eye is 2 to 2-1/2 inches behind the front face of the visor. In either case, the exit pupil diameter must be equal to or greater than 4 mm.

A telescope reticle must be provided consisting of two vertical reference lines approximately 1° apart arranged symmetrically about the measurement plane within ±0.1°. The reticle must be lighted. The intensity of light on the reticle must be variable in three discrete steps. A four position switch will provide an "off" position and three successive levels of illumination to the reticle. Provisions must be made so that these levels of illumination may be varied to more desirable levels after the sextant is put into operation.

The optics of the telescope shall be of astronomical quality. If the human eye is assumed to have a resolving power of 1 minute of arc, the product of the telescope magnification power and the telescope angular resolving power must be 1 minute of arc or less. The angular resolution of the telescope will be predicted upon its ability to resolve the line patterns of the National Bureau of Standards Test Chart of 1952 (reference: National Bureau of Standards Circular 533, Method for Determining the Resolving Power of Photographic lenses). The telescope must be of the erect image type. Coated optics will be used in the telescope and throughout the instrument to provide maximum light transmission and contrast.

4.0 Reflecting Surfaces

It is expected that a minimum of two reflecting surfaces will be utilized. These optical elements shall be mounted so that no discernible deformation is caused by the attitude of the instrument in either a 1 g field or a 0 g field. The reflecting surfaces will be alined so that the astronaut can make zero bias measurements while looking at a single star through both lines of sight.

The quality of all surfaces of optically active elements shall be sufficient to prevent degradation of the specified telescope resolution and specified instrument accuracy. The indexing optical element should reflect nominally 100 percent of its incident light while the horizon optical element should reflect and pass equal parts (50 percent) of its incident and reflected light.

5.0 Optical Filters

Optical filters shall be provided for possible use in both lines of sight. The density of the filters will be specified at a later date; however, their purpose is to provide the proper illumination and contrast between target pairs of star and star, star and lunar limb or landmark, and lunar limb and limb. The entire surface of both sides of the filters shall be sufficiently flat to prevent degradation of the specified telescope resolution or specified instrument accuracy. The wedge angle between the two sides of the filters shall be 5 arcsec or less, and the filter oriented to provide minimum measurement errors.

6.0 Indexing Mirror Drive

The rotating index mirror or prism shall have a minimum range of rotation from -3° to +35° which is equivalent to a sextant angle of -6° to +70°. A greater range of measurement is desirable if other design requirements are not compromised.

Rapid adjustment of the mirror shall be provided to reduce the time required for measuring and a fine adjustment shall be provided commensurate with the precision requirements of the instrument.

7.0 Angle Readout Display

The measured angle readout must be illuminated and easily read. The least count display must be 0.001 arcsec.

8.0 Operator - Instrument Accuracy Requirements

The accuracy requirements for the experienced operator-instrument combinations is a 1 σ of 10 arcsec or less. This requirement is for use in space, but will be construed as the requirements for the operator-instrument combination, fixed relative to the earth, sighting through the atmosphere but not through a window.

The fulfillment of this requirement will be demonstrated by the contractor in three steps:

(a) He will make a series of angle measurements between two known stars. He will compare the measured angle and the angle obtained from an ephemeris corrected for atmospheric

refraction and annual aberration, and the difference in values shall meet the 1 σ value of 10 arcsec.

(b) He will measure the angle between a star and the moon limb at known times. The time of the measurements shall be accurately determined to 0.1 sec. He will plot the data obtained. A quadratic curve fitted to these data by least squares techniques shall be considered the mean. The standard deviation from this mean must meet the 1 σ criterion.

(c) He will make precision measurements of the moon disk diameter at full moon by superimposing one moon limb on its opposite limb. The 1 σ criterion must be met.

9.0 Optical Calibration Requirements

An optical calibration of each instrument will be conducted by the contractor. This calibration will be observed by a properly qualified person designated by the Contracting Officer and the calibration data will accompany the delivery of each instrument. The calibration tools will be commensurate with calibration accuracy of ±1 arcsec. The calibration will be composed of three basic components as follows:

(a) The following calibration is required to determine the effectiveness of the readout mechanism. With the angular position of the indexing mirror determined, possibly by a collimator, the vernier control will be set at zero. The vernier control will then be turned away from zero by a minimum of 30 minutes of arc, then returned to zero. The position of the mirror will then be noted. This type of setting will be obtained 20 times by each of 3 individuals for a total of 60 settings. The standard deviation (1 σ) of the repeatability of the mirror position must be within 2 arcsec.

(b) All components, with the possible exception of the telescope and filters, will be used to calibrate the total measurement range (-6° to ±70°) in 1° increments. The calibration will be repeated three times. All data with zero bias removed will repeat within 6 arcsec (total). The measured and readout angles will agree within a 20 arcsec envelope.

(c) All components, with the possible exception of the telescope and filters, will be used to calibrate the measurement range of 32° to 33° in 0.1° increments. This calibration will be repeated three times. The data will be recorded and submitted with the instrument documentation.

(d) Zero bias of each filter will be determined.

10.0 Pressure Evacuation Testing

To insure that the instrument will operate properly at partial atmospheric pressures (3.5 psia and above) after being subjected to a hard vacuum, the instrument will be tested as follows. The complete instrument will be subjected to a pressure of 10^{-5} mm Hg for 48 hours. The instrument will then be examined for proper mechanical operation and for damage to the optical components. The instrument must also comply with the requirements contained in paragraph 2.0.

TABLE A - PRELIMINARY FLIGHT RATING TEST SCHEDULE
OF A HAND-HELD SPACE SEXTANT

Optical Calibration

Optical calibration will consist of those items included in paragraph 2.0(b), except that calibration increments will be 2°. All optical calibration data obtained during the flight rating tests with zero bias removed must be repeatable within 6 arcsec (total). The measured and readout angles will agree within ±10 arcsec.

Vibration Tests

All tests are to be performed at the g level, frequency, and amplitude indicated below. The sextant is also to be instrumented with accelerometers for a resonance search about three axes. The vibration tests are to be applied to three orthogonal sextant axes.

Approximate load in g	Oscillation mode, cps	Double amplitude of oscillation, in.
8	2,000	0.00004
	500	.0006
5	500	.0004
	100	.009
3	100	.006
	17	.2

Acceleration Tests

All acceleration is to be in the plus and minus directions along the axes and with the g level as indicated.

Longitudinal: 1-9.86 g varying linearly over 326 sec
20.4 g for 30 sec duration
Lateral: 9.86 g for 1 sec
6.12 g for 30 sec duration

Shock Tests

All shock tests to be performed in the plus and minus direction along the axes and at 50 percent of the g level, as indicated below. The instrument is then to be visually inspected, and if there is no significant damage, the shock tests are to be performed at 100 percent of the indicated g level in the plus and minus direction along the indicated axes.

Longitudinal:	40.8 g arbitrary pulse duration, half sine
	20.4 g for a 11 msec duration
Lateral:	20.4 g for a 11 msec duration

Note: The tests in Table A were conducted concurrently with the space-flight qualification test specified by the Gemini Program Office.

APPENDIX B

ERROR MODEL ANALYSIS

In this analysis, the individual sources for the error model of figure 5 are discussed. This analysis includes only those errors which vary with the magnitude of the measured angle and do not include bias errors that have a constant effect throughout the measurement range.

During the design phase of the sextant, the error sources were analyzed in the following manner.

A. Optical Errors: In general, errors introduced by misalinement of the optical surfaces will be fixed but will be reduced to an insignificant value by careful alinement procedures. The flatness and irregularity of the scanning mirror will be controlled to a quarter wavelength or better.

B. Eccentricity of Mirror Mounting: An off-axis condition of bearing mounting surfaces of the scanning mirror will be adjusted at assembly so that its error contribution is negligible. Lateral shift of the scanning mirror along its mounting axis does not contribute an error to the system.

C. Sector Gear Tooth to Tooth Spacing Error: The sector gear radius is 1.9 inches. The maximum tooth to tooth spacing error is $\pm 25 \times 10^{-6}$ inch, resulting in a shaft angular error of approximately ± 2.8 arcsec. Since the ratio of the change in indicated angle to the rotation of the mirror is 2/1, the sector gear error will be magnified by a factor of 2. The total contribution of the sector gear tooth spacing error is ± 5.6 arcsec.

D. Worm Shaft Mounting Eccentricity: The magnitude of the mounting eccentricity is a combination of the errors introduced by radial eccentricities in the worm shaft bearings and concentricity errors between the pitch circle of the worm and the bearing journal. During fabrication, each of the contributing factors was controlled to 50×10^{-6} inch. However, during assembly, the components were alined so as to minimize the total effect; consequently, after assembly, the eccentricity was 50×10^{-6} inch. This produced a cyclic maximum error of $\pm 25 \times 10^{-6}$ inch. With a pressure angle of 14.5° of worm gear profile, the $\pm 25 \times 10^{-6}$ inch eccentricity is reduced by a factor of the tangent of 14.5° and resulting sector gear contact point error is 6.25×10^{-6} inch. With a sector gear radius of approximately 1.9 inches, the angular error is equal to $6.25 \times 10^{-6} / 1.9 \times 4.85 \times 10^{-6} = 0.7$ arcsec. Since the worm gear error will be transmitted through the sector gear, and the sector gear errors are magnified by a factor of 2, the total error due to the worm shaft mounting eccentricity is 1.4 arcsec.

E. Worm Shaft Deviation From Helical Path: The deviation of the worm gear thread from the true helical path will be controlled to

$\pm 25\times10^{-6}$ inch. This error will have the same effect as the sector gear tooth to tooth spacing error except for an averaging factor which is a function of the number of contact points between the worm and the sector gear. Experimental data indicate that the error due to the worm shaft deviation from a true helical path was reduced by a factor of 2 because of the averaging effect, and the final maximum error was ± 2.8 arcsec or one half the sector gear tooth to tooth spacing error.

F. Worm Shaft Axial Play: Any motion of the worm shaft in the direction of its central axis introduces an instrument error equivalent to a tooth spacing or helical path deviation error. This motion is generally constrained by the close control of the axial play of the worm bearing and the antibacklash spring load of the gear on the worm shaft. To reduce this error further, the contractor chose a particular bearing out of several on the basis of minimum axial play and oriented the bearing to reduce the axial play. The contractor's measured data indicate that the worm shaft axial play is approximately $\pm 25\times10^{-6}$ inch. Therefore, the axial play maximum error was similar to the sector gear tooth to tooth error and was ± 5.6 arcsec.

G. Spur Gears Indexing Error (92/46 Gear Ratio): The indexing error for both the 92 tooth spur gear and the 46 tooth spur gear is 200×10^{-6} inch. The 92 tooth spur gear diameter is 1.0 inch and its angular error is $200\times10^{-6}/0.5 = 400\times10^{-6}$ radian = 82.7 arcsec. The ratio of spur gear rotation to scanning mirror rotation is 360° to 1°. This means that when the gear shaft is rotated 360°, the scanning mirror shaft changes by 1°. Therefore, the effective error of the 92 tooth spur gear is $2/360\times82.7 = 0.5$ arcsec. The 46 tooth spur gear diameter is approximately 0.5 inch and has shaft angular error of 800×10^{-6} radian or 165 arcsec. The ratio of the 46 tooth spur gear shaft rotation to scanning mirror shaft rotation is 720° to 1°. Therefore, the effective error of the 46 tooth spur gear is $1/360\times165 = 0.5$ arcsec. The maximum total error of these gears is 1.0 arcsec.

H. Spur Gears Indexing Error (94/47 Gear Ratio): As in the previous spur gear analysis, the indexing errors of the 94 tooth and 47 tooth spur gears are each assumed to be 200×10^{-6} inch. The indexing errors are additive. With the 94 tooth gear diameter of 1.0 inch, the shaft angular error is 82.7 arcsec. The ratio of gear rotation to scanning mirror rotation is 720°/1° and the measurement error is 0.2 arcsec.

The 47 tooth spur gear diameter is 0.5 inch and the shaft angular error is 165.4 arcsec. The ratio of gear rotation to scanning mirror rotation is 720°/0.5° and the resultant measurement error is 0.2 arcsec. The maximum error is 0.4 arcsec.

I. Spur Gears Indexing Error (90/18 Gear Ratio): The indexing errors of the 90 tooth and 18 tooth spur gears are each 200×10^{-6} inch. The 90 tooth gear diameter is approximately 1.0 inch. The shaft angular error is 82.7 arcsec. The ratio of gear rotation to scanning mirror rotation is 720°/0.5°, and the effective error is 0.1 arcsec.

The 18 tooth spur gear diameter is approximately 0.2 inch and the shaft angular error is 413 arcsec. The ratio of gear rotation to scanning mirror rotation is 720°/0.1°, and the effective error is 0.1 arcsec. The maximum error would be 0.2 arcsec.

J. Bevel Gears Indexing Error (42/42 Gear Ratio): The bevel gears are assumed to have a maximum indexing error of 200×10^{-6} inch. The pitch diameter of the gears is approximately 0.4 inch. The ratio of gear rotation to scanning mirror rotation is 720°/0.1°. The same analysis as that applied to the spur gears shows the effective error of the bevel gears is approximately 0.1 arcsec.

K. Counter Dial Readout Error: The readout dial of the sextant is marked to a least count of 3.6 arcsec (0.001°). The sextant operators are required to read to the nearest 1/2 division or 1.8 arcsec. The estimated maximum error during normal operation is 0.9 arcsec.

L. Overall Accuracy: In this analysis, the sextant accuracy is assumed to be the square root of the sum of the individual errors squared. This RSS value is 8.6 arcsec.

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TABLE I.- GENERAL CHARACTERISTICS OF SEXTANT

Characteristic	Normal eye relief eyepiece	Long eye relief eyepiece
Size (length × width × height, in.)	$6\frac{63}{64} \times 7\frac{1}{4} \times 6\frac{3}{64}$	$6\frac{51}{64} \times 7\frac{1}{4} \times 6\frac{3}{64}$
Weight, kg	2.778	2.665
Magnification	8.0X	4.6X
Field of view, deg	7	7
Exit pupil, mm	4	7
Eye relief, mm	18	59.7
Diopter adjustment	-3 to 5	-3 to 3
Resolution, arcsec	7.5	13.0
Image	Erect	Erect
Measurement range, deg	76	76

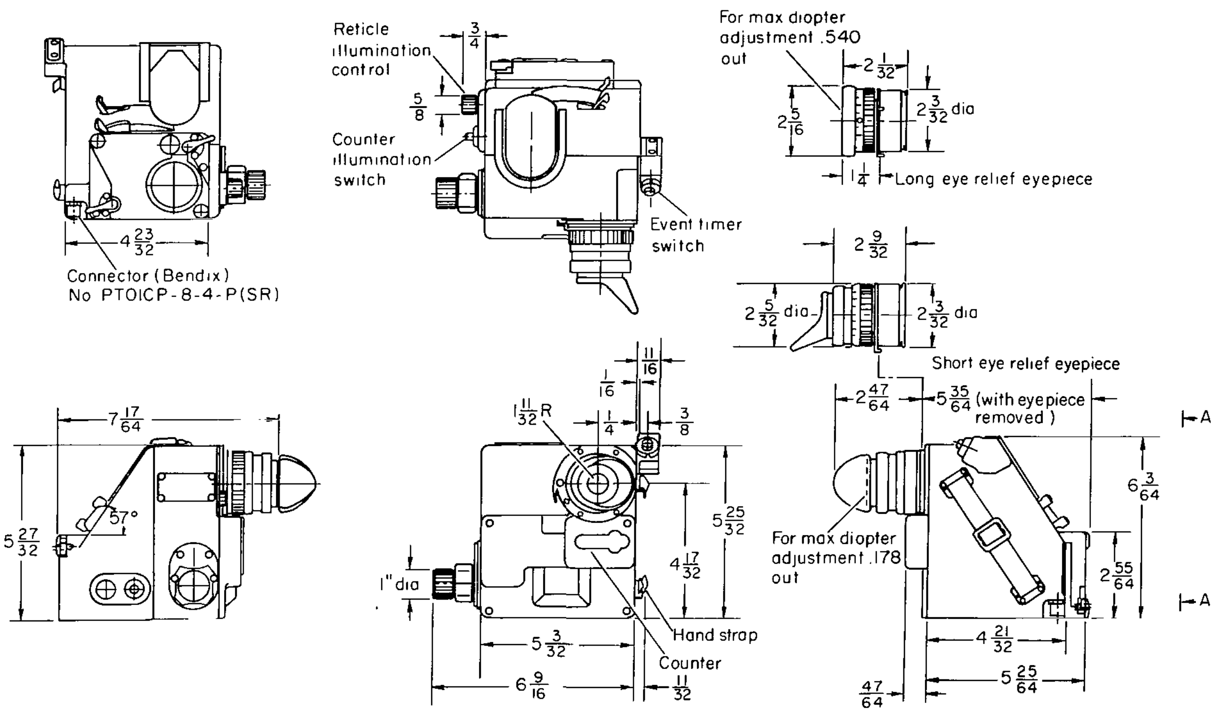

TABLE II.- SUMMARY OF ENVIRONMENTAL TESTS

	Test	
1	Shock	Longitudinal: ±30 g Lateral: approximately ±11 g along two remaining axes
2	Vibration	Sinusoidal: 30 min each axis at frequencies from 5 to 2000 cps Random tests: 15 min
3	Acceleration	Longitudinal: 1-10 g for 326 sec, 20 g for 30 sec Lateral: 10 g for 1 sec, 6 g/30 sec
4	Acoustic noise	130 dB for 10 min in line with optical axis; repeat with noise source in line with remaining two axes
5	Humidity	Humidity 95%, 160° F max, total test time is 240 hr, at each 24 hr period visual inspection and check for smooth operation
6	Temperature/pressure cycling and decompression	16 cycles where each cycle has a max. pressure = 1.47×10^{-8} psia, max. temp. = 200° F, min. temp. = 0° F
7	Low temperature	0° F for 2 hr, verify smooth control operation at the test environment
8	High temperature/100% oxygen atmosphere	100% O_2 at 5.5 psia and temp. of 160° F for 48 hr. For 30 min temp. of 200° F, return slowly to ambient conditions
9	Noxious odors and CO test	Exposed to O_2 at 1/3 atmosphere and 155° F for 72 hr - cooled and pressurized O_2 to 1 atmosphere, tested for CO and noxious odors

TABLE III.- SEXTANT, SERIAL NO. 2, CALIBRATION DATA OVER TOTAL-MEASUREMENT RANGE

Sextant angle setting	Calibration of bias error, arcsec			Sextant angle setting	Calibration of bias error, arcsec		
	First	Second	Third		First	Second	Third
-6	7	6	5	33	8	7	7
-5	6	3	4	34	7	7	8
-4	4	3	2	35	7	6	7
-3	7	7	8	36	6	4	5
-2	9	7	8	37	8	5	7
-1	4	2	3	38	6	3	4
0	0	0	0	39	10	8	9
1	8	6	8	40	8	9	9
2	7	6	8	41	9	9	8
3	4	3	4	42	8	7	8
4	2	3	1	43	9	9	8
5	7	5	6	44	9	8	8
6	7	7	4	45	11	11	12
7	9	8	10	46	10	10	9
8	7	7	7	47	9	10	12
9	7	6	8	48	8	11	9
10	6	7	7	49	11	13	11
11	9	10	10	50	11	10	11
12	9	9	8	51	6	4	4
13	7	7	7	52	6	4	5
14	7	7	7	53	11	10	14
15	13	13	13	54	12	10	11
16	13	13	13	55	13	15	14
17	14	15	16	56	10	11	13
18	11	12	12	57	10	8	8
19	11	10	12	58	8	9	8
20	6	7	8	59	16	16	15
21	4	5	7	60	15	15	15
22	5	4	3	61	11	10	11
23	8	8	10	62	9	10	9
24	9	7	9	63	15	16	14
25	9	8	8	64	16	16	16
26	7	7	7	65	16	18	17
27	9	6	7	66	14	16	16
28	6	4	5	67	16	17	17
29	9	6	8	68	16	16	16
30	7	4	4	69	18	19	18
31	6	4	4	70	19	19	19
32	5	4	5				

TABLE IV.- SEXTANT, SERIAL NO. 2, CALIBRATION DATA IN 0.1° INCREMENTS

Sextant angle setting	Calculation of bias error, arcsec		
	First	Second	Third
32.0	3	2	4
32.1	0	1	0
32.2	-2	-1	0
32.3	-1	0	-2
32.4	-1	0	-1
32.5	-1	0	1
32.6	1	1	1
32.7	3	2	4
32.8	8	6	6
32.9	5	6	7
33.0	5	7	5

TABLE V.- OPTICAL FILTER CORRECTION DATA

Filter	Neutral density	Correction value, arcsec
(a) Sextant serial number 1		
Fixed line of sight	1.0 1.6	1 -5
Scanning line of sight	1.0 1.3	4 -3
(b) Sextant serial number 2		
Fixed line of sight	1.0 1.6	-4 -3
Scanning line of sight	1.0 1.3	-5 -2

TABLE VI.- ZERO BIAS DATA

Day	Target	Operator	Positive direction: Mean error, arcsec	Positive direction: 1 σ, arcsec	Negative direction: Mean error, arcsec	Negative direction: 1 σ, arcsec	Remarks
2	Spica	1	0.9	1.8	2.9	5.9	Beginning of session
		2	0	5.7	4.3	3.0	
		3	-5.0	4.1	.7	4.0	
		4	-7.9	4.7	-12.2	4.1	
3	Polaris	1	-10.8	6.7	-17.3	6.4	Beginning of session
		2	-6.5	5.9	-6.5	8.2	
		3	-15.8	3.2	-14.4	2.3	
		4	-11.5	3.0	-11.5	6.9	
		1	1.4	2.0	-3.6	3.6	End of session
		2	-7.9	3.0	0	3.6	
		3	-5.0	4.1	-4.3	4.7	
		4	-4.3	5.9	-4.3	5.9	
		1	-0.7	5.3			Long eye relief optics
		2					
		3	-10.8	2.6			
		4	0.7	6.9			
4		1	-10.0	4.0	-7.2	7.6	Beginning of session
		2	-9.0	3.2	-17.3	7.8	
		3	-13.7	4.0	-12.2	3.2	
		4	-12.2	7.5	-16.6	5.5	
		1	-12.2	2.0	-5.0	3.2	End of session
		2	-13.7	1.6	-19.4	6.0	
		3	-20.9	4.7	-16.6	3.2	
	Alkaid	4	-11.5	4.0	-16.6	6.0	

TABLE VII.- FUNCTIONAL VERIFICATION TEST DATA

[All data in seconds of arc unless otherwise noted. Zero bias corrections are the average of the predata and postdata measurements and are appropriate to the positive or negative direction of scanning mirror drive direction.]

Day	Operator	Targets	Nominal measured angle	1 σ of measurements	Uncorrected mean error	Corrections to data: Calibration	Corrections to data: Filter	Corrections to data: Zero bias	Corrected mean error	Remarks
1	3	Spica and Arcturus	32°48'	11.4	2.4	-12.5			-10.1	No zero bias data available on this day
	4		32°48'	9.0	-7.3	-12.5			-19.8	
	1		32°48'	14.0	-2.2	-12.5			-14.7	
	3	Phecda and Dubhe	10°26'	8.4	-.7	-2.0			-2.7	
	2		10°25'	18.7	.3	-2.0			-1.7	
	4	Polaris and Alioth	34°42'	8.4	17.0	-16.0			1.0	
	1		34°42'	11.0	21.9	-16.0			5.9	
	2		34°42'	24.6	9.7	-16.0			-6.3	
	1	Far limb and Denebola	29°18'	11.9	26.4	-8.4	-4.0		14.0	Both filters in primary line of sight
	4		29°13'	4.1	2.3	-8.4	-4.0		-10.1	
	3		29°11'	6.6	28.6	-8.4	-4.0		16.2	
	2		29° 7'	24.4	41.1	-8.4	-4.0		28.7	
2	1	Polaris and Alioth	34°42'	13.0	34.9	-16.0		-0.9	18.0	
	2		34°42'	19.8	19.0	-16.0		0	3.0	
	3		34°42'	6.2	16.7	-16.0		5.0	5.7	
	4		34°42'	13.7	20.3	-16.0		7.9	12.2	
	1	Regulus and near limb	8°50'	8.0	5.9	-1.7	1.0	-.9	4.3	Both filters in scanning line of sight
	2		8°55'	16.1	-12.5	-1.7	1.0	0	-13.2	
	3		8°59'	7.5	-6.7	-1.7	1.0	5.0	-2.4	
	4		9° 2'	6.1	-1.0	-1.7	1.0	7.9	6.2	
	1	Far limb and Denebola	15°32'	4.7	4.7	-4.2	-4.0	-2.9	-6.4	Both filters in primary line of sight
	3		15°28'	5.7	12.9	-4.2	-4.0	-.7	4.0	
	2		15°22'	15.3	3.6	-4.2	-4.0	-4.3	-8.9	
	4		15°18'	4.6	13.1	-4.2	-4.0	12.2	17.1	
	1	Lunar limb and limb	0°33'	7.7	1.8	0	5.0	-2.9	3.9	ND 1.0 filter in both lines of sight
	3		0°33'	4.3	.5	0	5.0	-.7	4.8	
	2		0°33'	4.5	-1.2	0	5.0	-4.3	-.5	
	4		0°33'	4.4	1.4	0	5.0	12.2	18.6	
	1	Spica and Arcturus	32°48'	11.6	25.7	-12.5		-.9	12.3	
	3		32°48'	5.9	16.1	-12.5		5.0	8.6	
	2		32°48'	14.2	12.5	-12.5		0	0	
	4		32°48'	7.3	21.5	-12.5		7.9	16.9	
3	1	Polaris and Alioth	34°42'	4.7	14.2	-16.0		4.7	2.9	
	2		34°42'	13.7	6.1	-16.0		7.2	-2.7	
	3		34°42'	3.4	11.2	-16.0		10.4	5.6	
	4		34°42'	6.1	9.5	-16.0		7.9	1.4	
	1	Regulus and near limb	22°19'	6.4	1.2	-5.8	1.0	4.7	1.1	Both filters in secondary line of sight
	2		22°22'	11.7	-16.7	-5.8	1.0	7.2	-14.3	
	3		22°26'	9.6	-.6	-5.8	1.0	10.4	5.0	
	4		22°28'	7.3	-4.7	-5.8	1.0	7.9	-1.6	

TABLE VII.- FUNCTIONAL VERIFICATION TEST DATA - Concluded

Day	Operator	Targets	Nominal measured angle	1 σ of measurements	Uncorrected mean error	Corrections to data			Corrected mean error	Remarks
						Calibration	Filter	Zero bias		
3	1	Spica and far limb	32°18'	12.7	2.9	-11.8	1.0	10.5	2.6	Both filters in secondary line of sight
	2		32°14'	5.0	4.0	-11.8	1.0	3.3	-3.5	
	3		32°10'	4.4	15.2	-11.8	1.0	9.4	13.8	
	4		32° 7'	12.8	23.3	-11.8	1.0	7.9	20.4	
	1	Lunar limb and limb	0°33'	4.9	-10.2	0	5.0	10.5	5.3	ND 1.0 filter in both lines of sight
	2		0°33'	7.5	-11.0	0	5.0	3.3	-2.7	
	3		0°33'	16.9	-25.0	0	5.0	9.4	10.6	
	4		0°33'	7.2	-9.0	0	5.0	7.9	3.9	
	1	Spica and Arcturus	32°48'	5.5	15.0	-12.5	---	4.7	7.2	
	2		32°48'	15.9	13.1	-12.5	---	7.2	7.8	
	3		32°48'	4.2	3.5	-12.5	---	10.4	1.4	
	4		32°48'	6.4	11.1	-12.5	---	7.9	6.5	
	4	Spica and Arcturus	32°48'	13.1	-3.7	-12.5	---	-.7	-16.9	Long eye relief optics
	1		32°48'	22.9	3.3	-12.5	---	.7	-8.5	
	3		32°48'	13.9	7.4	-12.5	---	10.8	5.7	
4	1	Spica and far limb	18°25'	9.1	3.0	-4.8	1.0	6.1	5.3	Both filters in scanning line of sight
	2		18°22'	8.1	3.4	-4.8	1.0	18.4	18.0	
	3		18°20'	9.5	10.7	-4.8	1.0	14.4	21.3	
	4		18°17'	9.6	7.6	-4.8	1.0	16.6	20.4	
	1	Lunar limb and limb	0°33'	3.8	-31.2	0	5.0	6.1	-20.1	ND 1.0 filter in both lines of sight
	2		0°33'	3.5	-24.4	0	5.0	18.4	-1.0	
	3		0°33'	4.8	-13.3	0	5.0	14.4	6.1	
	4		0°33'	7.0	-22.1	0	5.0	16.6	-.5	
	1	Near limb and Denebola	17°15'	7.7	.7	-4.6	-4.0	11.2	3.3	Both filters in primary line of sight
	2		17°17'	6.5	2.5	-4.6	-4.0	11.4	5.3	
	3		17°21'	4.3	-6.9	-4.6	-4.0	17.3	1.8	
	4		17°23'	10.6	-9.3	-4.6	-4.0	11.9	-6.0	
	1	Polaris and Alioth	34°42'	5.2	13.8	-16.0	---	11.2	9.0	
	2		34°42'	6.6	10.4	-16.0	---	11.4	5.8	
	3		34°42'	8.1	13.2	-16.0	---	17.3	14.5	
	4		34°42'	4.9	16.3	-16.0	---	11.9	12.2	
	1	Dubhe and Phecda	10°26'	6.1	-2.4	-2.1	---	11.2	6.7	
	2		10°26'	10.3	-8.4	-2.1	---	11.4	.9	
	3		10°26'	11.1	3.9	-2.1	---	17.3	19.1	
	4	Alioth and Alkaid	10°28'	7.4	-4.9	-2.1	---	11.9	4.9	

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